Performance Measurement and Visualization on the Cray XT

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Cray Toolset Design Goals

- **Assist** the user with application performance analysis and optimization
  - Help user identify important and meaningful information from potentially massive data sets
  - Help user identify problem areas instead of just reporting data
  - Bring optimization knowledge to a wider set of users

- Focus on **ease** of use and **intuitive** user interfaces
  - Automatic program instrumentation
  - Automatic analysis

- Target **scalability** issues in all areas of tool development
  - Data management
    - Storage, movement, presentation

The Cray Performance Analysis Framework

- Supports traditional post-mortem performance analysis
  - Automatic identification of performance problems
    - Indication of causes of problems
    - Suggestions of modifications for performance improvement
  - Transitioning to an optimization guidance tool

- **CrayPat**
  - **pat_build**: automatic instrumentation (no source code changes needed)
  - **run-time library** for measurements (transparent to the user)
  - **pat_report** for performance analysis reports
  - **pat_help**: online help utility

- **Cray Apprentice^2**
  - Graphical performance analysis and visualization tool

The Cray Performance Analysis Framework (2)

- **CrayPat**
  - Instrumentation of optimized code
  - No source code modification required
  - Data collection transparent to the user
  - Text-based performance reports
  - Derived metrics
  - Performance analysis

- **Cray Apprentice2**
  - Performance data visualization tool
  - Call tree view
  - Source code mappings

Collecting Performance Data

- **When** performance measurement is triggered
  - **External agent** (asynchronous)
    - **Sampling**
      - Timer interrupt
      - Hardware counters overflow
  - **Internal agent** (synchronous)
    - **Code instrumentation**
      - Event based
      - Automatic or manual instrumentation
- **How** performance data is recorded
  - **Profile** ::= Summation of events over time
    - run time summarization (functions, call sites, loops, …)
  - **Trace file** ::= Sequence of events over time

Multiple Dimensions of Scalability

- Millions of lines of code
  - **Automatic profiling analysis**
    - Identifies top time consuming routines
    - Automatically creates instrumentation template customized to your application
- Lots of processes/threads
  - **Load imbalance** analysis
    - Identifies computational code regions and synchronization calls that could benefit most from load balance optimization
    - Estimates savings if corresponding section of code were balanced
- Long running applications
  - Detection of **outliers** (coming soon)

Performance Analysis with Cray Tools

- Important performance statistics:
  - Top time consuming routines
  - Load balance across computing resources
  - Communication overhead
  - Cache utilization
  - FLOPS
  - Vectorization (SSE instructions)
  - Ratio of computation versus communication

Application Instrumentation with pat_build

- **No** source code or makefile **modification** required
  - **Automatic instrumentation** at group (function) level
    - Groups: mpi, io, heap, math SW, …

- Performs link-time instrumentation
  - **Requires object files**
  - Instruments optimized code
  - Generates stand-alone instrumented program
  - Preserves original binary
  - Supports **sample-based** and **event-based** instrumentation

CrayPat API - For Fine Grain Instrumentation

- Fortran

```
include "pat_apif.h"
…
call PAT_region_begin(id, "label", ierr)
do i = 1,n
…
enddo
call PAT_region_end(id, ierr)
```

- C & C++

```
include <pat_api.h>
…
ierr = PAT_region_begin(id, "label");
< code segment >
ierr = PAT_region_end(id);
```

CrayPat API - Disable/Enable Recording

- Fortran

```
include "pat_apif.h"
…
call PAT_record(0) ! Disable
do i = 1,n
…
enddo
call PAT_record(1) ! Enable
```

- C & C++

```
include <pat_api.h>
…
ierr = PAT_record(0); /* Disable */
< code segment >
ierr = PAT_record(1); /* Enable */
```

Where to Run Instrumented Applications

- **MUST run on Lustre** (/work/… , /lus/…, /scratch/…, etc.)
- Number of files used to store raw data
  - 1 file created for program with 1 – 256 processes
  - $\sqrt{n}$ files created for program with 257 – *n* processes
  - Ability to customize with **PAT_RT_EXPFILE_MAX**

pat_report

- Performs data conversion
  - Combines information from binary with raw performance data
- Performs analysis on data
- Generates text report of performance results
- Formats data for input into Cray Apprentice^2

Automatic Profiling Analysis

- **Analyze** the performance data and **direct the user** to meaningful information

- **Simplifies** the procedure to instrument and collect performance data for novice users

- Based on a two phase mechanism
  1. **Automatically** detects the most time consuming functions in the application and feeds this information back to the tool for further (and focused) data collection

  2. Provides performance information on the most significant parts of the application

Steps to Collecting Performance Data

- Access performance tools software

```
% module load perftools
```

- Build application keeping .o files (CCE: -h keepfiles)

```
% make clean
% make
```

- Instrument application for automatic profiling analysis
  - You should get an instrumented program a.out+pat

```
% pat_build -O apa a.out
```

- Run application to get top time consuming routines
  - You should get a performance file (“<sdatafile>.xf”) or multiple files in a directory <sdatadir>

```
% aprun … a.out+pat   (or  qsub <pat script>)
```

Steps to Collecting Performance Data (2)

- Generate report and .apa instrumentation file

```
% pat_report -o my_sampling_report [<sdatafile>.xf |
  <sdatadir>]
```

- Inspect .apa file and sampling report

- Verify if additional instrumentation is needed
  - Check the sampling report for possible regions to instrument with the CrayPat API

Sampling Output (Table 1)

```
Notes for table 1:
...
Table 1:  Profile by Function

 Samp % | Samp |  Imb.  |   Imb.  |Group
        |      |  Samp  | Samp %  | Function
        |      |        |         |  PE='HIDE'

 100.0% |  775 |     -- |      -- |Total
|------------------------------------------
|  94.2% |  730 |     -- |      -- |USER
||-----------------------------------------
||  43.4% |  336 |   8.75 |    2.6% |mlwxyz_
||  16.1% |  125 |   6.28 |    4.9% |half_
||   8.0% |   62 |   6.25 |    9.5% |full_
||   6.8% |   53 |   1.88 |    3.5% |artv_
||   4.9% |   38 |   1.34 |    3.6% |bnd_
||   3.6% |   28 |   2.00 |    6.9% |currenf_
||   2.2% |   17 |   1.50 |    8.6% |bndsf_
||   1.7% |   13 |   1.97 |   13.5% |model_
||   1.4% |   11 |   1.53 |   12.2% |cfl_
||   1.3% |   10 |   0.75 |    7.0% |currenh_
||   1.0% |    8 |   5.28 |   41.9% |bndbo_
||   1.0% |    8 |   8.28 |   53.4% |bndto_
||=========================================
|   5.4% |   42 |     -- |      -- |MPI
||-----------------------------------------
||   1.9% |   15 |   4.62 |   23.9% |mpi_sendrecv_
||   1.8% |   14 |  16.53 |   55.0% |mpi_bcast_
||   1.7% |   13 |   5.66 |   30.7% |mpi_barrier_
|==========================================
```

Samp % provides absolute percentages

Sampling Output (Table 2)

```
Table 2:  Profile by Group, Function, and Line

 Samp % | Samp |  Imb.  |  Imb.   |Group
        |      |  Samp  | Samp %  | Function
        |      |        |         |  Source
        |      |        |         |   Line
        |      |        |         |    PE='HIDE'

 100.0% |  777 |    -- |      -- |Total
|-------------------------------------------------
|  94.2% |  732 |    -- |      -- |USER
||------------------------------------------------
||  43.4% |  337 |    -- |      -- |mlwxyz
3|        |      |       |         | ldr/mhd3d/src/mlwxyz.f
|||-----------------------------------------------
4|||   2.1% |   16 |  1.47 |    8.9% |line.39
4|||   2.8% |   22 |  2.25 |    9.7% |line.78
4|||   1.2% |    9 |  1.09 |   11.3% |line.116
4|||   1.4% |   11 |  1.22 |   10.5% |line.129
4|||   2.2% |   17 |  2.12 |   11.5% |line.139
. . .
4|||   2.7% |   21 |  0.84 |    4.0% |line.568
4|||   1.3% |   10 |  1.72 |   14.8% |line.604
4|||   2.4% |   19 |  0.72 |    3.7% |line.634
|||===============================================
||================================================
||  16.1% |  125 |    -- |      -- |half
3|        |      |       |         | ldr/mhd3d/src/half.f
|||-----------------------------------------------
4|||   5.4% |   42 |  6.41 |   13.8% |line.28
4|||  10.7% |   83 |  5.91 |    6.9% |line.40
|||===============================================
||   8.0% |   62 |    -- |      -- |full
3|        |      |       |         | ldr/mhd3d/src/full.f
|||-----------------------------------------------
4|||   8.0% |   62 |  6.31 |    9.6% |line.22
|||===============================================
. . .
||================================================
|  5.4% |   42 |    -- |      -- |MPI
||------------------------------------------------
||  1.9% |   15 |  4.62 |  23.9% |mpi_sendrecv_
||------------------------------------------------
||================================================
||  1.8% |   14 | 16.53 |  55.0% |mpi_bcast
||  1.7% |   13 |  5.66 |  30.7% |mpi_barrier_
|=================================================
```

APA File Example

```
#  You can edit this file, if desired, and use it
#  to reinstrument the program for tracing like this:
#
#           pat_build -O mhd3d.Oapa.x+4125-401sdt.apa
#
#  These suggested trace options are based on data from:
#
#       /home/crayadm/ldr/mhd3d/run/mhd3d.Oapa.x+4125-401sdt.ap2,
        /home/crayadm/ldr/mhd3d/run/mhd3d.Oapa.x+4125-401sdt.xf

# ----------------------------------------------------------------------

#       HWPC group to collect by default.

  -Drtenv=PAT_RT_HWPC=1  # Summary with instructions metrics.

# ----------------------------------------------------------------------

#       Libraries to trace.

  -g mpi

# ----------------------------------------------------------------------

#       User-defined functions to trace, sorted by % of samples.
#       Limited to top 200. A function is commented out if it has < 1%
#       of samples, or if a cumulative threshold of 90% has been reached,
#       or if it has size < 200 bytes.

 #  Note: -u should NOT be specified as an additional option.
```

```
# 43.37%  99659 bytes
         -T mlwxyz_

# 16.09%  17615 bytes
         -T half_

#  6.82%  6846 bytes
         -T artv_

#  1.29%  5352 bytes
         -T currenh_

#  1.03%  25294 bytes
         -T bndbo_

#  Functions below this point account for less than 10% of samples.


#  1.03%  31240 bytes
#         -T bndto_

. . .

# ----------------------------------------------------------------------

  -o mhd3d.x+apa                  # New instrumented program.

  /work/crayadm/ldr/mhd3d/mhd3d.x  # Original program.
```

-g tracegroup (subset)

adios	Adaptable I/O System API
armci	Aggregate Remote Memory Copy
blas	Basic Linear Algebra subprograms
caf	Co-Array Fortran (Cray CCE compiler only)
chapel	Chapel language compile and runtime library API
dmapp	Distributed Memory Application API for Gemini network
hdf5	manages extremely large and complex data collections
heap	dynamic heap
io	includes stdio and sysio groups
lapack	Linear Algebra Package
mpi	MPI
omp	OpenMP API and runtime library API (CCE and PGI only)
shmem	SHMEM
upc	Unified Parallel C (Cray CCE compiler only)

For a full list, please see man pat_build

Steps to Collecting Performance Data (2)

- Instrument application for further analysis (a.out+apa)

```
% pat_build -O <apafile>.apa
```

- Run application

```
% aprun … a.out+apa  (or  qsub <apa script>)
```

- Generate text report and visualization file (.ap2)

```
% pat_report -o my_text_report.txt [<datafile>.xf | <datadir>]
```

- View report in text and/or with Cray Apprentice^2

```
% app2 <datafile>.ap2
```

pat_report: Flat Profile

```
Table 1:  Profile by Function Group and Function

 Time % |       Time |Imb. Time |   Imb.  | Calls |Group
        |            |          | Time %  |       | Function
        |            |          |         |       |  PE='HIDE'

 100.0% | 104.593634 |       -- |      -- | 22649 |Total
|------------------------------------------------------------
|  71.0% |  74.230520 |       -- |      -- | 10473 |MPI
||-----------------------------------------------------------
||  69.7% |  72.905208 | 0.508369 |   0.7% |   125 |mpi_allreduce_
||   1.0% |   1.050931 | 0.030042 |   2.8% |    94 |mpi_alltoall_
||===========================================================
|  25.3% |  26.514029 |       -- |      -- |    73 |USER
||-----------------------------------------------------------
||  16.7% |  17.461110 | 0.329532 |   1.9% |    23 |selfgravity_
||   7.7% |   8.078474 | 0.114913 |   1.4% |    48 |ffte4_
||===========================================================
|   2.5% |   2.659429 |       -- |      -- |   435 |MPI_SYNC
||-----------------------------------------------------------
||   2.1% |   2.207467 | 0.768347 |  26.2% |   172 |mpi_barrier_(sync)
||===========================================================
|   1.1% |   1.188998 |       -- |      -- | 11608 |HEAP
||-----------------------------------------------------------
||   1.1% |   1.166707 | 0.142473 |  11.1% |  5235 |free
|============================================================
```

pat_report: Message Stats by Caller

```
Table 4:  MPI Message Stats by Caller

    MPI Msg |MPI Msg |  MsgSz |  4KB<= |Function
      Bytes |   Count |   <16B |  MsgSz | Caller
            |         |  Count |  <64KB |  PE[mmm]
            |         |        |  Count |

 15138076.0 | 4099.4 |  411.6 | 3687.8 |Total
|------------------------------------------------
| 15138028.0 | 4093.4 |  405.6 | 3687.8 |MPI_ISEND
||-----------------------------------------------
||  8080500.0 | 2062.5 |   93.8 | 1968.8 |calc2_
3|            |        |        |        | MAIN_
||||---------------------------------------------
4|||  8216000.0 | 3000.0 | 1000.0 | 2000.0 |pe.0
4|||  8208000.0 | 2000.0 |     -- | 2000.0 |pe.9
4|||  6160000.0 | 2000.0 |  500.0 | 1500.0 |pe.15
||||=============================================
||  6285250.0 | 1656.2 |  125.0 | 1531.2 |calc1_
3|            |        |        |        | MAIN_
||||---------------------------------------------
4|||  8216000.0 | 3000.0 | 1000.0 | 2000.0 |pe.0
4|||  6156000.0 | 1500.0 |     -- | 1500.0 |pe.3
4|||  6156000.0 | 1500.0 |     -- | 1500.0 |pe.5
||||=============================================
. . .
```

Using Hardware Performance Counters

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Hardware Performance Counters

- AMD Opteron Hardware Performance Counters
  - **Four** 48-bit performance counters.
    - Each counter can monitor a single event
      - Count specific processor events
        - the processor increments the counter when it detects an occurrence of the event
        - (e.g., cache misses)
      - Duration of events
        - the processor counts the number of processor clocks it takes to complete an event
        - (e.g., the number of clocks it takes to return data from memory after a cache miss)
  - Time Stamp Counters (TSC)
    - Cycles (user time)

PAPI Predefined Events

- Common set of events deemed relevant and useful for application performance tuning
  - Accesses to the memory hierarchy, cycle and instruction counts, functional units, pipeline status, etc.
  - The “papi_avail” utility shows which predefined events are available on the system – execute on compute node
- PAPI also provides access to native events
  - The “papi_native_avail” utility lists all AMD native events available on the system – execute on compute node
- Information on PAPI and AMD native events
  - pat_help counters
  - man papi_counters
  - For more information on AMD counters:
    - http://www.amd.com/us-en/assets/content_type/white_papers_and_tech_docs/26049.PDF

Hardware Counters Selection

- PAT_RT_HWPC <set number> | <event list>
  - Specifies hardware counter events to be monitored
    - A set number can be used to select a group of predefined hardware counters events (recommended)
      - CrayPat provides 19 groups on the Cray XT systems
    - Alternatively a list of hardware performance counter event names can be used
      - Both formats can be specified at the same time, with later definitions overriding previous definitions
      - A statistical (**multiplexing**) approach is used when more than 4 events are provided
    - Hardware counter events are not collected by default

Hardware Counters Overhead Elimination

```
Hardware performance counter events:
  PAPI_L1_DCM  Level 1 data cache misses
  CYCLES_RTC   User Cycles (approx, from rtc)
  PAPI_L1_DCA  Level 1 data cache accesses
  PAPI_TLB_DM  Data translation lookaside buffer misses
  PAPI_FP_OPS  Floating point operations

Estimated minimum overhead per call of a traced function,
  which was subtracted from the data shown in this report
  (for raw data, use the option:  -s overhead=include):
    PAPI_L1_DCM       8.040  misses
    PAPI_TLB_DM       0.005  misses
    PAPI_L1_DCA     474.080  refs
    PAPI_FP_OPS       0.000  ops
    CYCLES_RTC     1863.680  cycles
    Time              0.693  microseconds
```

PAT_RT_HWPC=1 (Summary with TLB)

```
  PAPI_TLB_DM  Data translation lookaside buffer misses
  PAPI_L1_DCA  Level 1 data cache accesses
  PAPI_FP_OPS  Floating point operations
  DC_MISS      Data Cache Miss
  User_Cycles  Virtual Cycles
========================================================================
USER
------------------------------------------------------------------------
  Time%                                               98.3%
  Time                                              4.434402 secs
  Imb.Time                                                -- secs
  Imb.Time%                                               --
  Calls                          0.001M/sec           4500.0 calls
  PAPI_L1_DCM                   14.820M/sec         65712197 misses
  PAPI_TLB_DM                    0.902M/sec          3998928 misses
  PAPI_L1_DCA                  333.331M/sec       1477996162 refs
  PAPI_FP_OPS                  445.571M/sec       1975672594 ops
  User time (approx)             4.434 secs      11971868993 cycles  100.0%Time
  Average Time per Call                             0.000985 sec
  CrayPat Overhead : Time         0.1%
  HW FP Ops / User time        445.571M/sec       1975672594 ops   4.1%peak(DP)
  HW FP Ops / WCT              445.533M/sec
  Computational intensity         0.17 ops/cycle        1.34 ops/ref
  MFLOPS (aggregate)          1782.28M/sec
  TLB utilization               369.60 refs/miss       0.722 avg uses
  D1 cache hit,miss ratios       95.6% hits             4.4% misses
  D1 cache utilization (misses)  22.49 refs/miss       2.811 avg hits
========================================================================
```

PAT_RT_HWPC=1

Flat profile data

Hard counts

Derived metrics

PAT_RT_HWPC=2 (L1 and L2 Metrics)

```
========================================================================
USER
------------------------------------------------------------------------
  Time%                                                   98.3%
  Time                                                 4.436808 secs
  Imb.Time                                                   -- secs
  Imb.Time%                                                  --
  Calls                           0.001M/sec             4500.0 calls
  DATA_CACHE_REFILLS:
    L2_MODIFIED:L2_OWNED:
    L2_EXCLUSIVE:L2_SHARED        9.821M/sec           43567825 fills
  DATA_CACHE_REFILLS_FROM_SYSTEM:
    ALL                          24.743M/sec          109771658 fills
  PAPI_L1_DCM                    14.824M/sec           65765949 misses
  PAPI_L1_DCA                   332.960M/sec         1477145402 refs
  User time (approx)              4.436 secs        11978286133 cycles  100.0%Time
  Average Time per Call                                0.000986 sec
  CrayPat Overhead : Time          0.1%
  D1 cache hit,miss ratios        95.5% hits                4.5% misses
  D1 cache utilization (misses)   22.46 refs/miss          2.808 avg hits
  D1 cache utilization (refills)   9.63 refs/refill        1.204 avg uses
  D2 cache hit,miss ratio         28.4% hits               71.6% misses
  D1+D2 cache hit,miss ratio      96.8% hits                3.2% misses
  D1+D2 cache utilization         31.38 refs/miss          3.922 avg hits
  System to D1 refill            24.743M/sec          109771658 lines
  System to D1 bandwidth       1510.217MB/sec         7025386144 bytes
  D2 to D1 bandwidth            599.398MB/sec         2788340816 bytes
========================================================================
```

PAT_RT_HWPC=5 (Floating point mix)

```
================================================================================
USER
--------------------------------------------------------------------------------
  Time%                                             98.4%
  Time                                          4.426552 secs
  Imb.Time                                            -- secs
  Imb.Time%                                           --
  Calls                      0.001M/sec           4500.0 calls
  RETIRED_MMX_AND_FP_INSTRUCTIONS:
    PACKED_SSE_AND_SSE2    454.860M/sec       2013339518 instr
  PAPI_FML_INS             156.443M/sec        692459506 ops
  PAPI_FAD_INS             289.908M/sec       1283213088 ops
  PAPI_FDV_INS               7.418M/sec         32834786 ops
  User time (approx)         4.426 secs      11950955381 cycles  100.0%Time
  Average Time per Call                         0.000984 sec
  CrayPat Overhead : Time   0.1%
  HW FP Ops / Cycles                                0.17 ops/cycle
  HW FP Ops / User time    446.351M/sec       1975672594 ops   4.1%peak(DP)
  HW FP Ops / WCT          446.323M/sec
  FP Multiply / FP Ops                             35.0%
  FP Add / FP Ops                                  65.0%
  MFLOPS (aggregate)       1785.40M/sec
================================================================================
```

PAT_RT_HWPC=12 (QC Vectorization)

```
========================================================================
USER
------------------------------------------------------------------------
  Time%                                                 98.3%
  Time                                               4.434163 secs
  Imb.Time                                                 -- secs
  Imb.Time%                                                --
  Calls                            0.001M/sec          4500.0 calls
  RETIRED_SSE_OPERATIONS:
    SINGLE_ADD_SUB_OPS:
    SINGLE_MUL_OPS                                          0 ops
  RETIRED_SSE_OPERATIONS:
    DOUBLE_ADD_SUB_OPS:
    DOUBLE_MUL_OPS               225.224M/sec       998097162 ops
  RETIRED_SSE_OPERATIONS:
    SINGLE_ADD_SUB_OPS:
    SINGLE_MUL_OPS:OP_TYPE                                  0 ops
  RETIRED_SSE_OPERATIONS:
    DOUBLE_ADD_SUB_OPS:
    DOUBLE_MUL_OPS:OP_TYPE  445.818M/sec      1975672594 ops
  User time (approx)               4.432 secs  11965243964 cycles  99.9%Time
  Average Time per Call                              0.000985 sec
  CrayPat Overhead : Time      0.1%
========================================================================
```

Vectorization Example

```
========================================================================
USER / calc2_
------------------------------------------------------------------------
  Time%                                             28.2%
  Time                                           0.600875 secs
  Imb.Time                                       0.069872 secs
  Imb.Time%                                         11.9%
  Calls                        864.9 /sec           500.0 calls
  RETIRED_SSE_OPERATIONS:
    SINGLE_ADD_SUB_OPS:
    SINGLE_MUL_OPS                                      0 ops
  RETIRED_SSE_OPERATIONS:
    DOUBLE_ADD_SUB_OPS:
    DOUBLE_MUL_OPS           369.139M/sec       213408500 ops
  RETIRED_SSE_OPERATIONS:
    SINGLE_ADD_SUB_OPS:
    SINGLE_MUL_OPS:OP_TYPE                              0 ops
  RETIRED_SSE_OPERATIONS:
    DOUBLE_ADD_SUB_OPS:
    DOUBLE_MUL_OPS:OP_TYPE   369.139M/sec       213408500 ops
  User time (approx)           0.578 secs  1271875000 cycles  96.2%Time
```

When compiled with fast:

```
========================================================================
USER / calc2_
------------------------------------------------------------------------
  Time%                                             24.3%
  Time                                           0.485654 secs
  Imb.Time                                       0.146551 secs
  Imb.Time%                                         26.4%
  Calls                        0.001M/sec           500.0 calls
  RETIRED_SSE_OPERATIONS:
    SINGLE_ADD_SUB_OPS:
    SINGLE_MUL_OPS                                      0 ops
  RETIRED_SSE_OPERATIONS:
    DOUBLE_ADD_SUB_OPS:
    DOUBLE_MUL_OPS           208.641M/sec       103016531 ops
  RETIRED_SSE_OPERATIONS:
    SINGLE_ADD_SUB_OPS:
    SINGLE_MUL_OPS:OP_TYPE                              0 ops
  RETIRED_SSE_OPERATIONS:
    DOUBLE_ADD_SUB_OPS:
    DOUBLE_MUL_OPS:OP_TYPE   415.628M/sec       205216531 ops
  User time (approx)           0.494 secs  1135625000 cycles  100.0%Time
```

How do I interpret these derived metrics?

- The following thresholds are guidelines to identify if optimization is needed:
  - **Computational Intensity:** **< 0.5 ops/ref**
    - This is the ratio of FLOPS by L&S
    - Measures how well the floating point unit is being used
  - **FP Multiply / FP Ops** or **FP Add / FP Ops**: **< 25%**
  - **Vectorization:** **< 1.5**

Memory Hierarchy Thresholds

- **TLB utilization: < 90.0%**
  - Measures how well the memory hierarchy is being utilized with regards to TLB
  - This metric depends on the computation being single precision or double precision
    - A page has 4 Kbytes. So, one page fits 512 double precision words or 1024 single precision words
  - TLB utilization < 1 indicates that not all entries on the page are being utilized between two TLB misses
- **Cache utilization: < 1 (D1 or D1+D2)**
  - A cache line has 64 bytes (8 double precision words or 16 single precision words)
  - **Cache utilization < 1** indicates that not all entries on the cache line are being utilized between two cache misses
- **D1 cache hit (or miss) ratios: < 90% (> 10%)**
- **D1 + D2 cache hit (or miss) ratios: < 92% (> 8%)**
  - D1 and D2 caches on the Opteron are complementary
  - This metric provides a view of the Total Cache hit (miss) ratio

Profile Visualization with Cray Apprentice^2

Luiz DeRose
Programming Environments Director
Cray Inc.

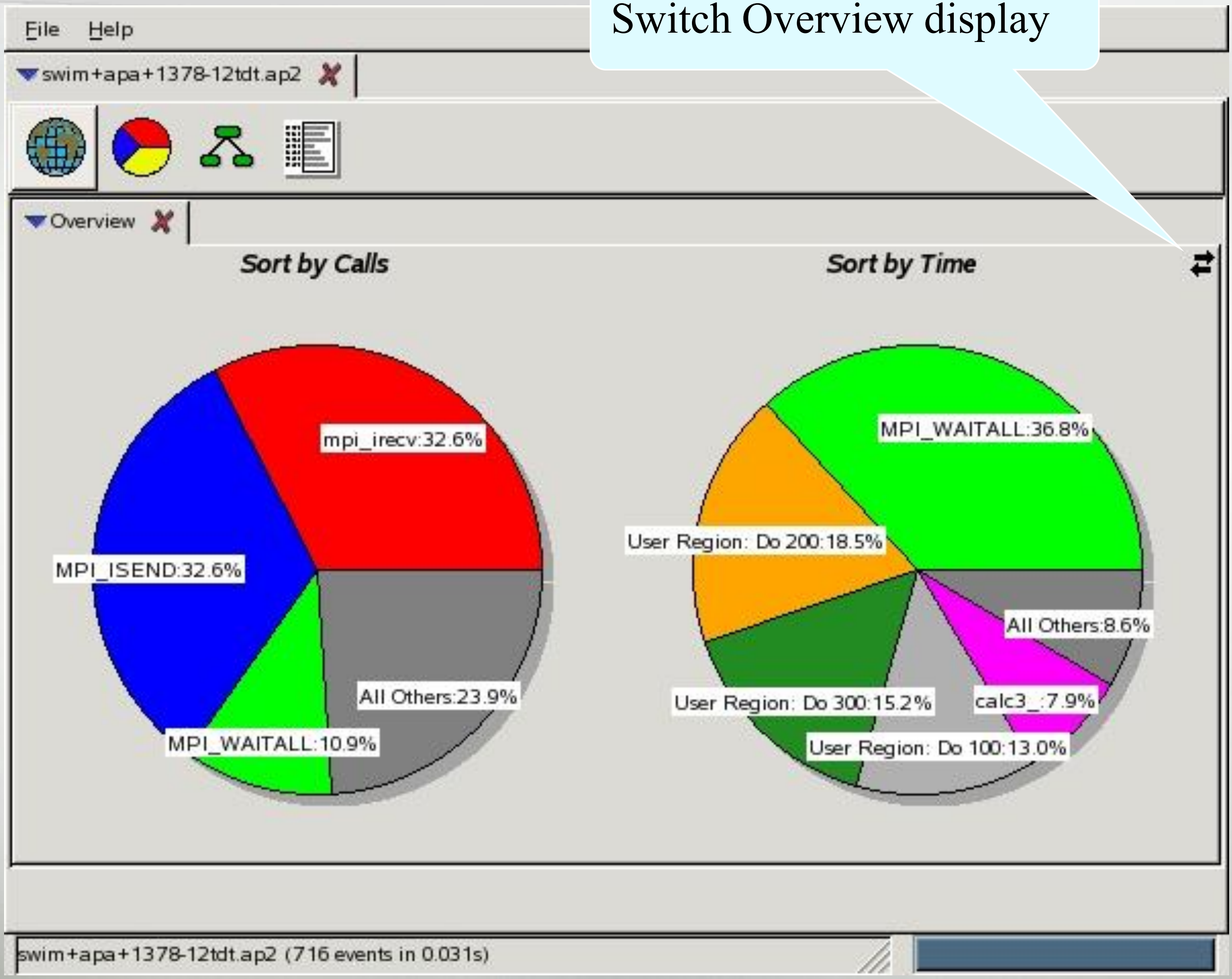
Cray Apprentice^2

- Call graph profile
- Communication statistics
- Time-line view
  - Communication
  - I/O
- Activity view
- Pair-wise communication statistics
- Text reports
- Source code mapping

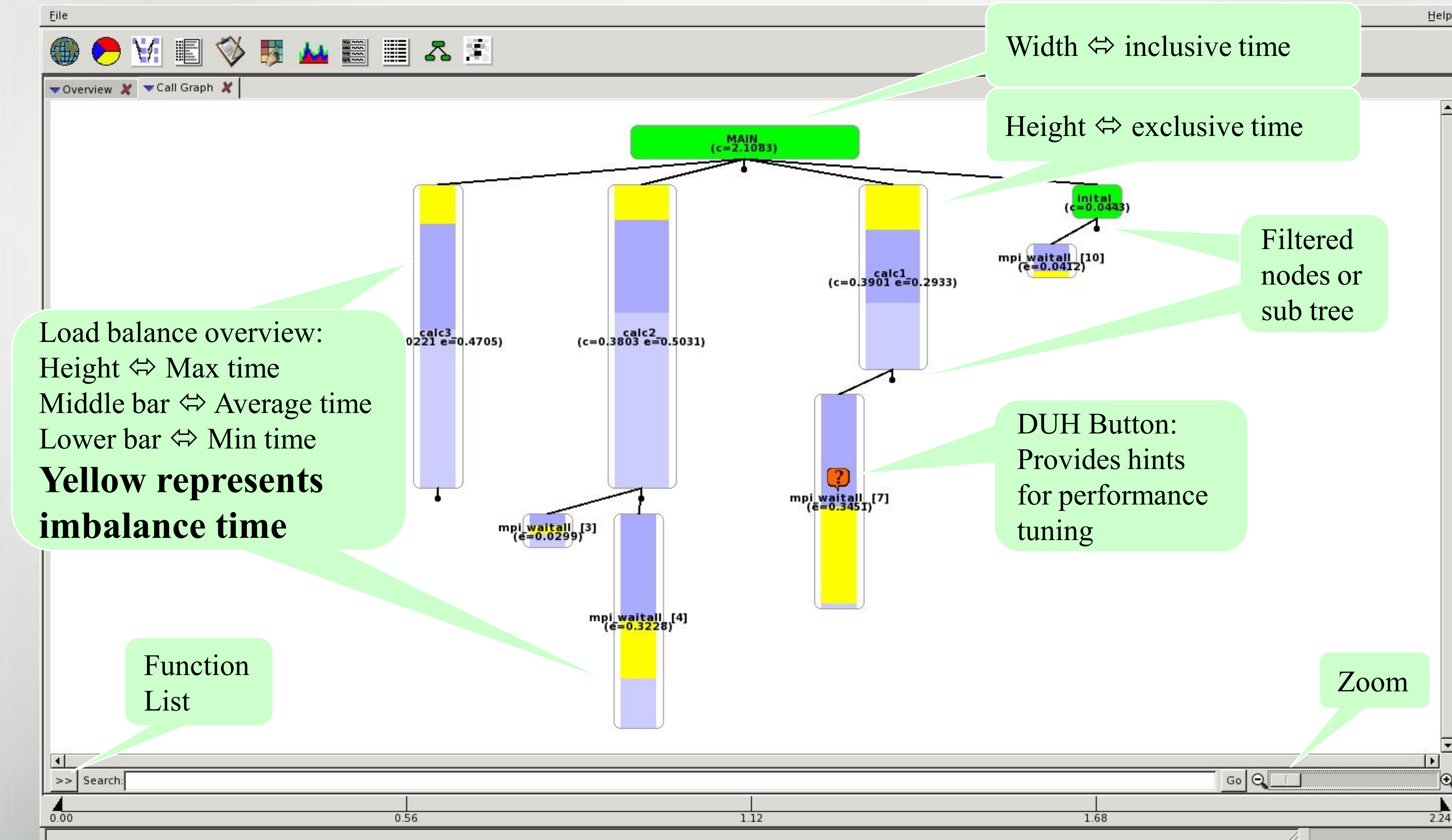
- Cray Apprentice^2
- is target to help and correct:
  - Load imbalance
  - Excessive communication
  - Network contention
  - Excessive serialization
  - I/O Problems

Statistics Overview

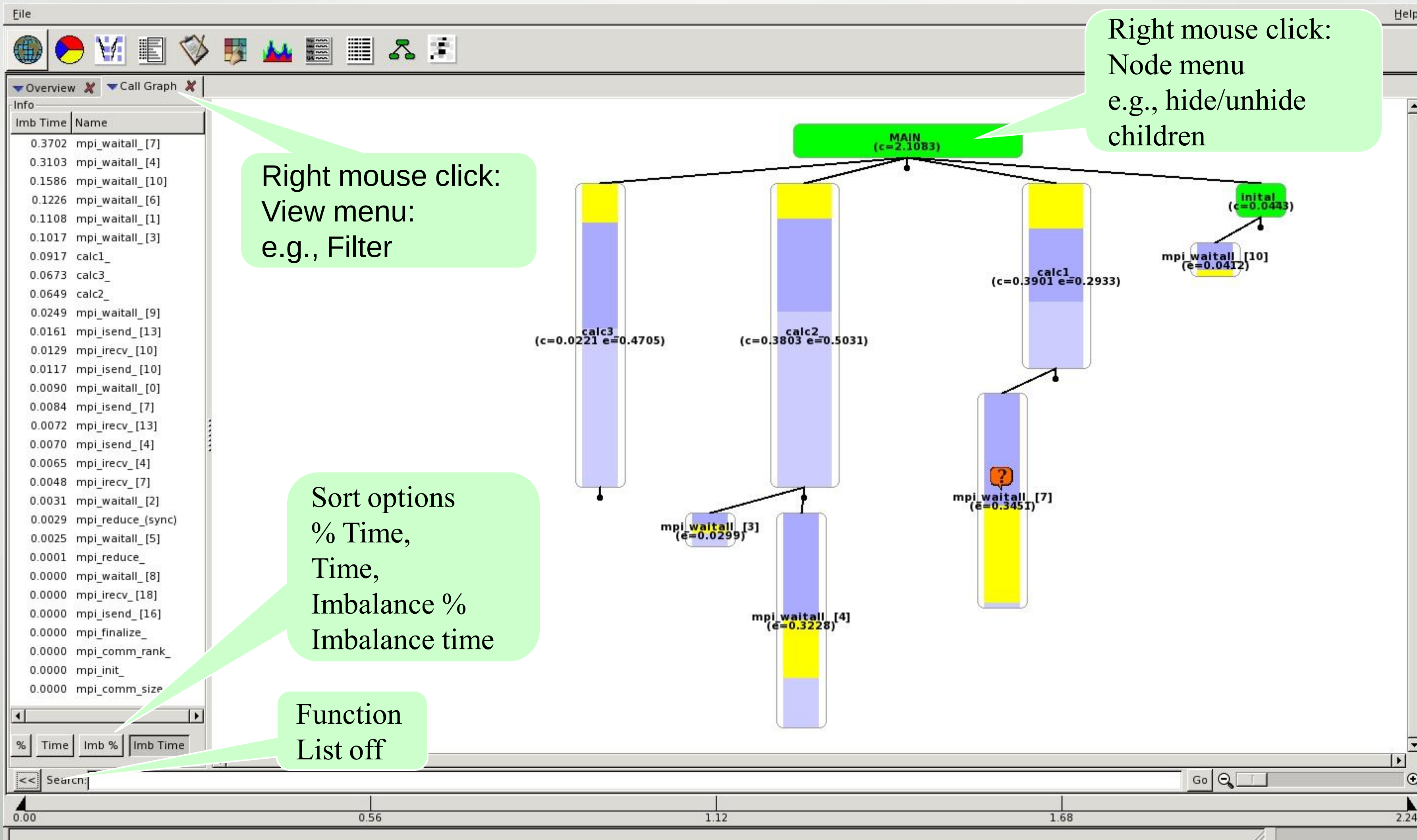
Switch Overview display



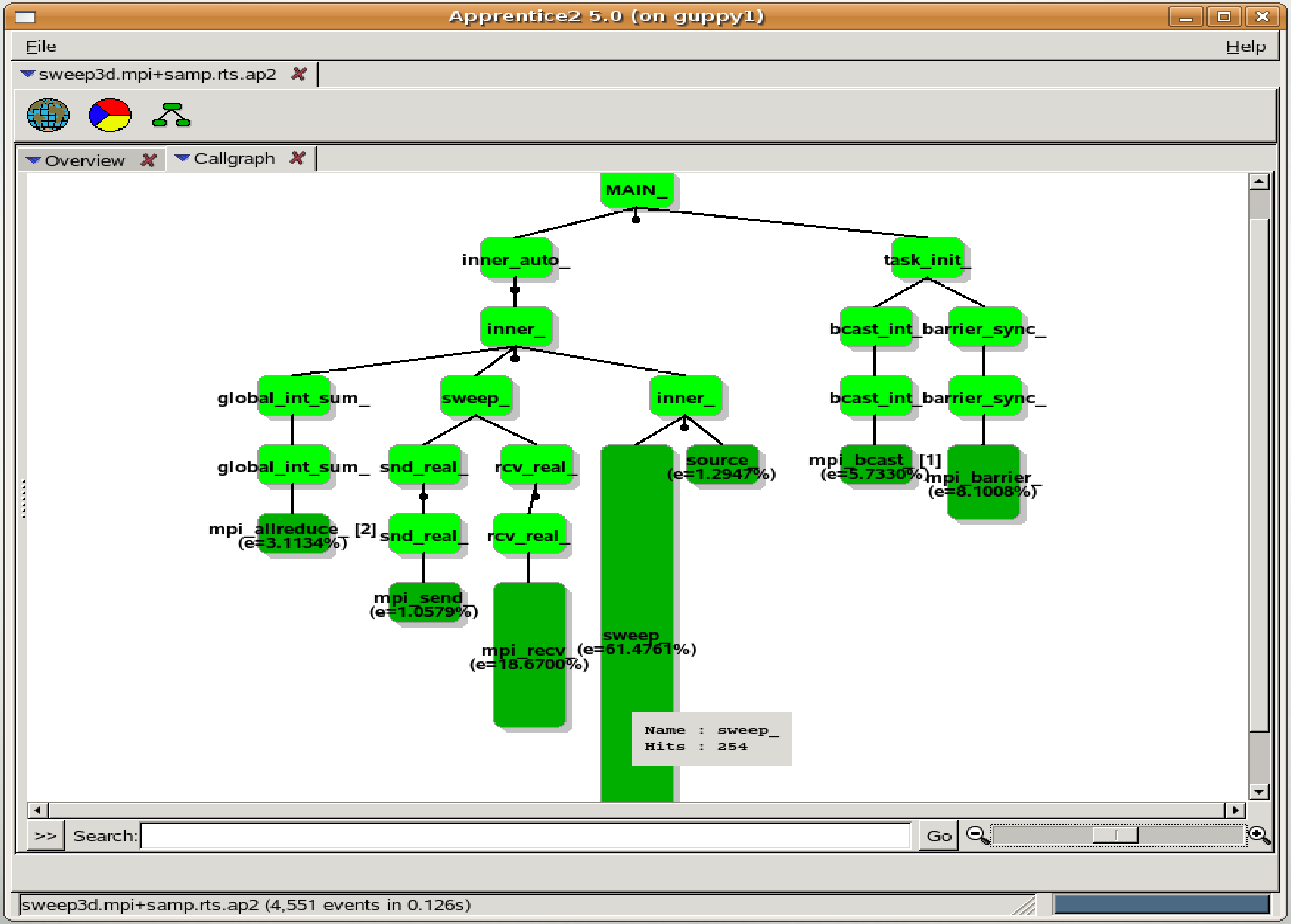
Call Tree View



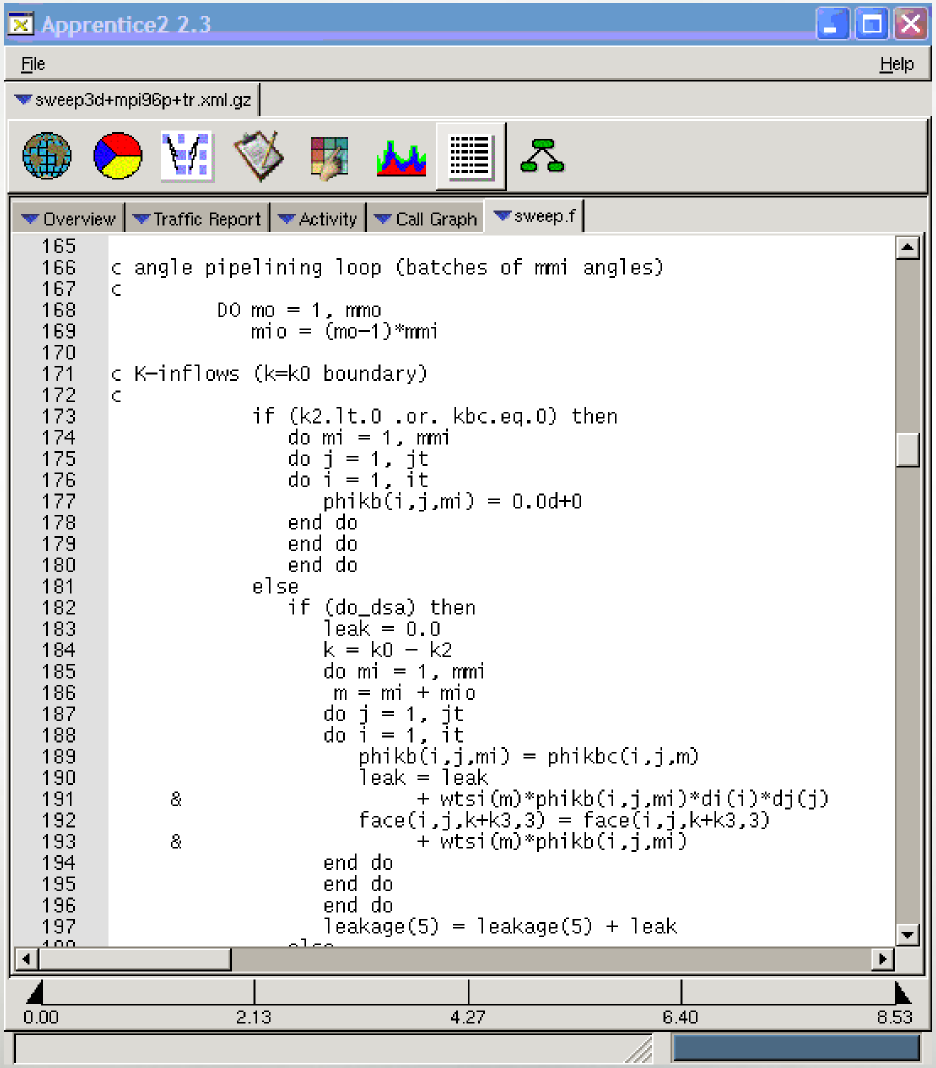
Call Tree View – Function List



Apprentice^2 Call Tree View of Sampled Data



Source Mapping from Call Tree



Detecting Load Imbalance on the Cray XT

Luiz DeRose
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Cray Inc.

Motivation for Load Imbalance Analysis

- Increasing system software and architecture complexity
  - Current trend in high end computing is to have systems with tens of thousands of processors
    - This is being accentuated with multi-core processors

- Applications have to be very well balanced in order to perform at scale on these MPP systems
  - Efficient application scaling includes a balanced use of requested computing resources

- Desire to minimize computing resource “waste”
  - Identify slower paths through code
  - Identify inefficient “stalls” within an application

Cray Tools Load Imbalance Support

- Very few performance tools focus on load imbalance
  - Need standard metrics
  - Need intuitive way of presentation

- CrayPat support:
  - MPI sync time
  - Imbalance time and %
  - MPI rank placement suggestions
  - OpenMP Performance Metrics

- Cray Apprentice^2 support:
  - Load imbalance visualization

MPI Sync Time

- Measure load imbalance in programs instrumented to trace MPI functions to determine if MPI ranks arrive at collectives together
- Separates potential load imbalance from data transfer
- Sync times reported by default if MPI functions traced
- If desired, PAT_RT_MPI_SYNC=0 deactivates this feature

Profile with Load Distribution by Groups

```
Table 1:  Profile by Function Group and Function

 Time % |        Time |  Imb. Time |   Imb.  |     Calls |Group
        |             |            | Time %  |           | Function
        |             |            |         |           |  PE='HIDE'

 100.0% | 513.581345 |         -- |      -- | 368418.8 |Total
|------------------------------------------------------------------
|  69.5% | 356.710479 |         -- |      -- |  37064.0 |USER
||-----------------------------------------------------------------
||  24.9% | 127.809860 |  34.800347 |  21.5% |      1.0 |main
||  23.7% | 121.692894 |  30.797216 |  20.3% |    480.0 |momtum_
||   7.8% |  40.231832 |  14.622935 |  26.8% |    480.0 |cnuity_
||   6.1% |  31.135595 |  16.354488 |  34.6% |  34174.0 |mod_xc_xctilr_
||   5.9% |  30.404372 |  14.887689 |  33.0% |    482.0 |hybgen_
||   1.1% |   5.435825 |   2.256039 |  29.4% |   1446.0 |dpudpv_
||=================================================================
|  24.7% | 127.038044 |         -- |      -- | 325626.8 |MPI
||-----------------------------------------------------------------
||  23.0% | 117.877116 | 307.988571 |  72.6% |  79473.6 |mpi_waitall_
||   1.4% |   7.203319 |   5.428131 |  43.1% |  79470.8 |mpi_startall_
||=================================================================
|   5.8% |  29.832822 |         -- |      -- |   5728.0 |MPI_SYNC
||-----------------------------------------------------------------
||   4.9% |  25.147203 |  30.818426 |  55.3% |   2814.0 |mpi_allreduce_(sync)
|==================================================================
```

Imbalance Time

- Metric based on execution time
- It is dependent on the type of activity:
  - User functions

    Imbalance time = Maximum time – Average time
  - Synchronization (Collective communication and barriers)

    Imbalance time = Average time – Minimum time
- Identifies computational code regions and synchronization calls that could benefit most from load balance optimization
- Estimates how much overall program time could be saved if corresponding section of code had a perfect balance
  - Represents upper bound on “potential savings”
  - Assumes other processes are waiting, not doing useful work while slowest member finishes

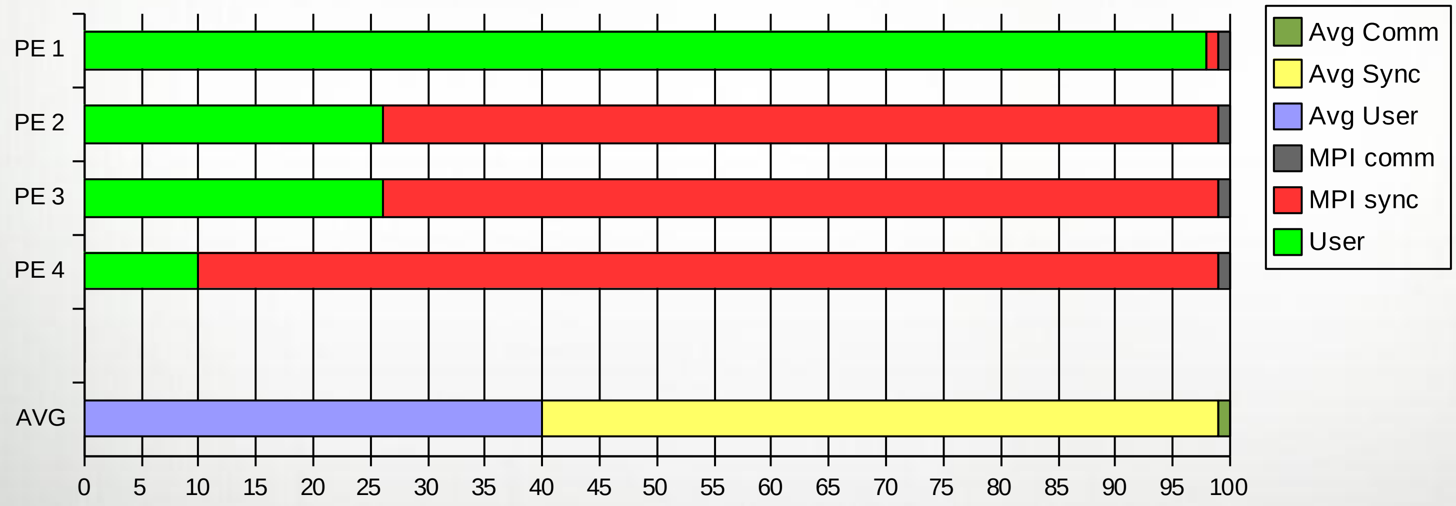
Load balance metric - rationale

Between two barriers

User: Imb = Max-Avg = 99-40 = 59

MPI Sync: Avg = 59

MPI Sync+Comm: Avg-Min = 60-1 = 59

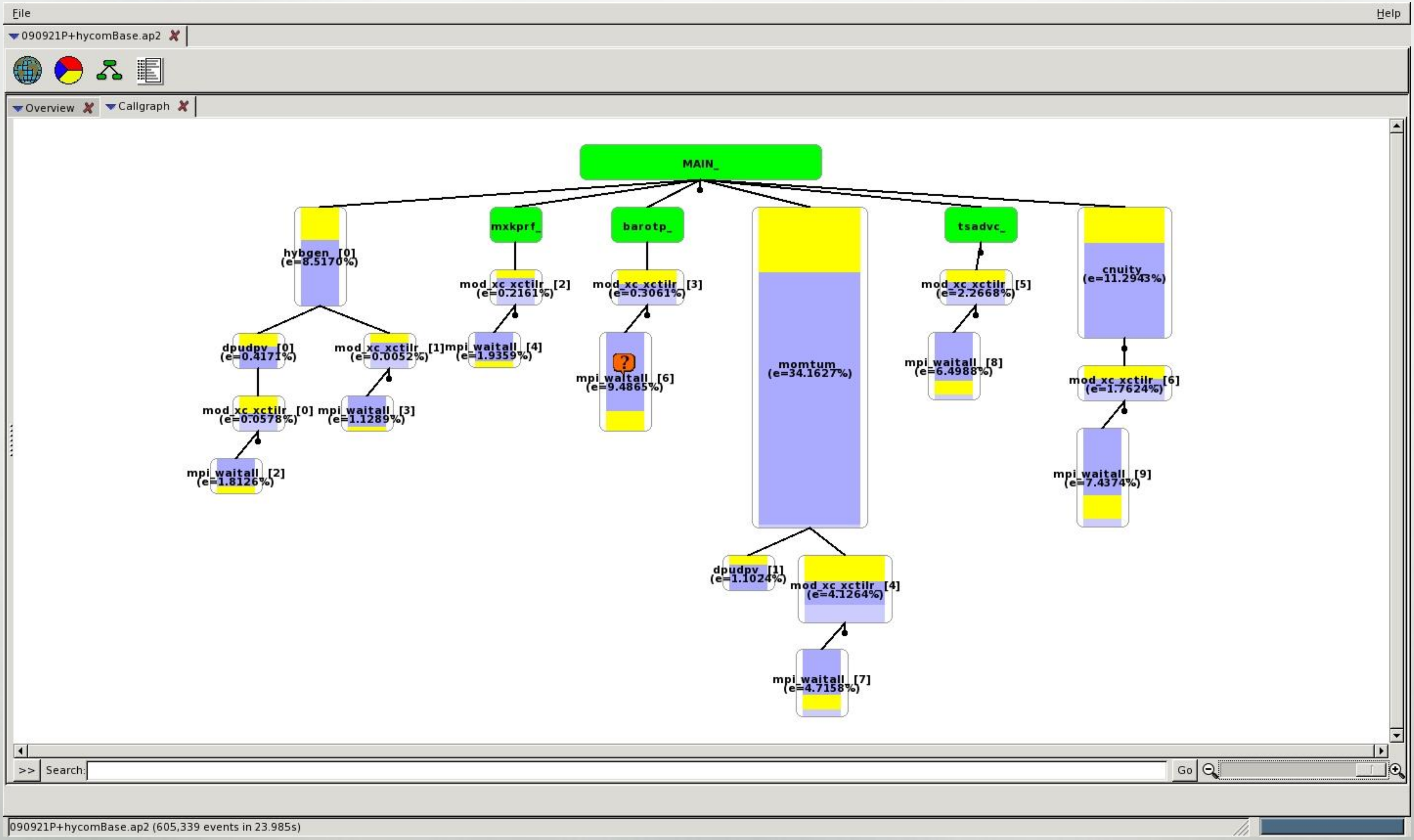


Imbalance %

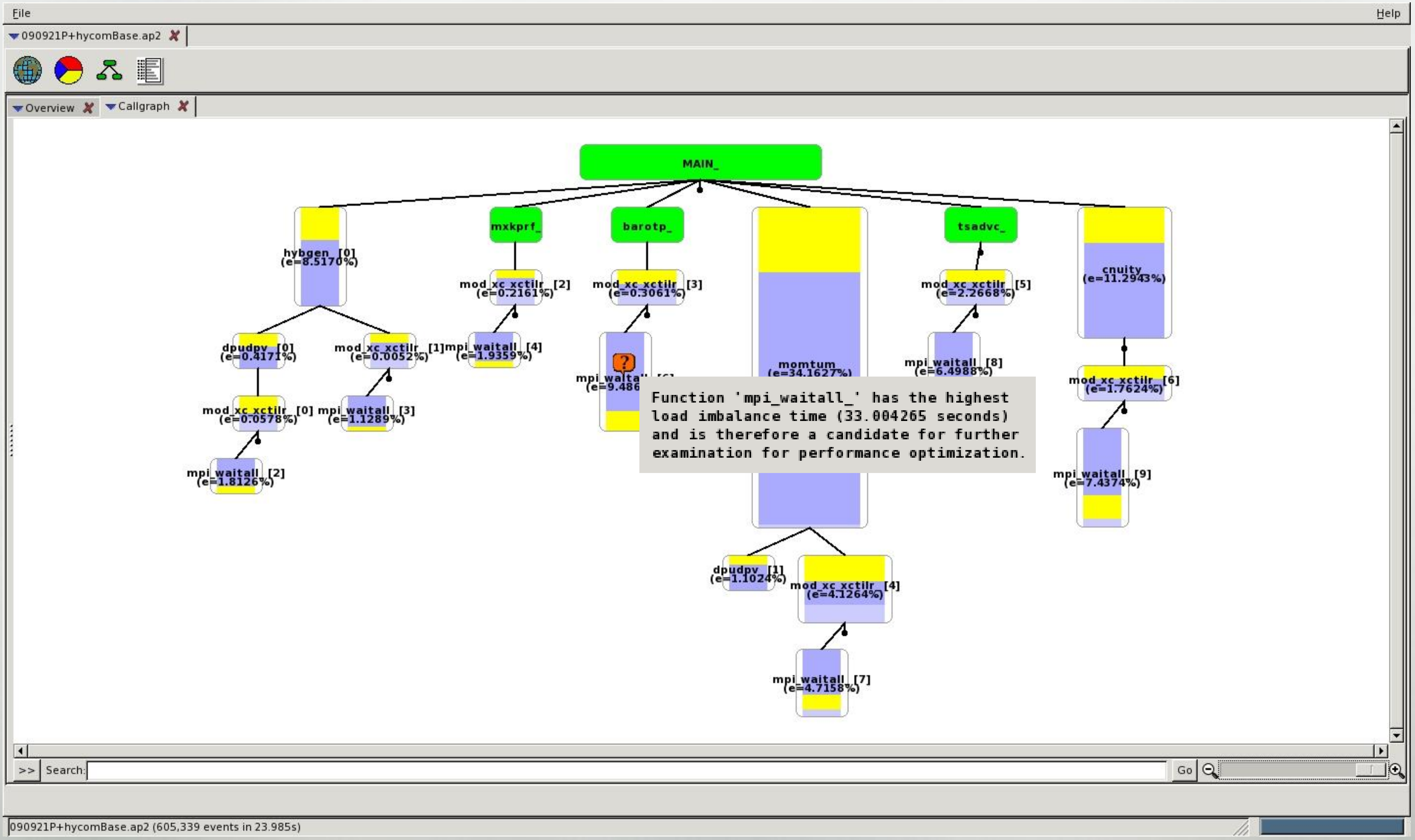
$$\text{Imbalance\%} = 100 \text{ X } \frac{\text{Imbalance time}}{\text{Max Time}} \text{ X } \frac{N}{N - 1}$$

- Represents % of resources available for parallelism that is "wasted"
- Corresponds to % of time that rest of team is not engaged in useful work on the given function
- Perfectly balanced code segment has imbalance of 0%
- Serial code segment has imbalance of 100%

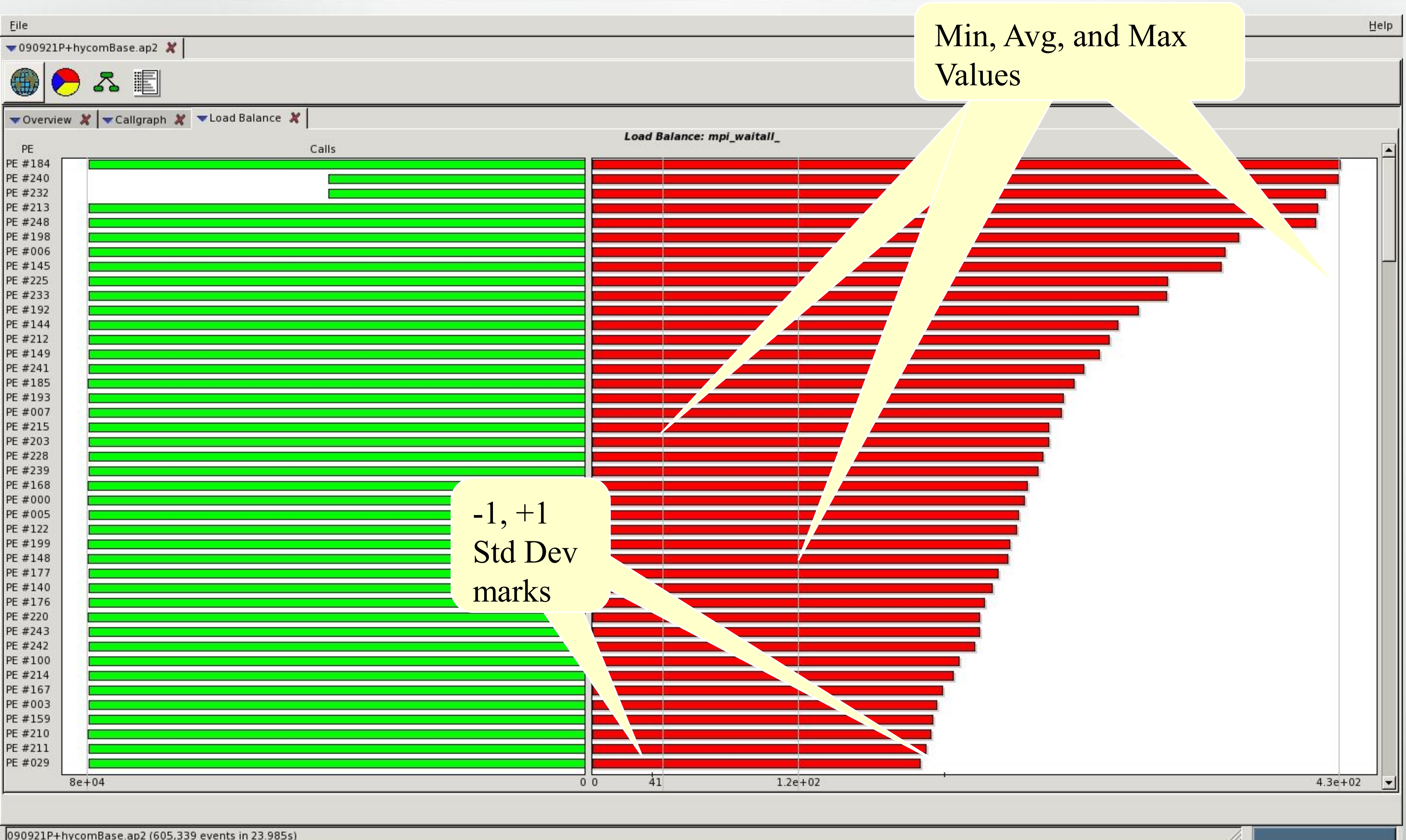
Call Tree Visualization (Hycom)



Call Tree Visualization (Hycom)

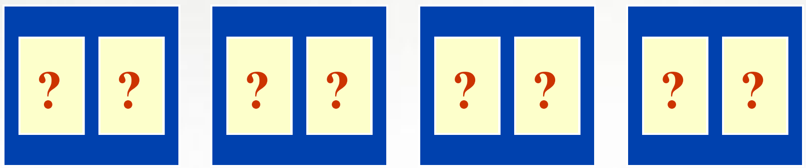


Load Balance Distribution



MPI Rank Reorder

- MPI rank placement with environment variable



  - ➢ Distributed placement
  - ➢ SMP style placement
  - ➢ Folded rank placement
  - ➢ User provided rank file

MPI Rank Placement Suggestions

- When to use?
  - Point-to-point communication consumes significant fraction of the program time and have a significant imbalance
    - pat_report -O mpi_sm_rank_order ...
  - When there seems to be a load imbalance of another type
    - Can get a suggested rank order file based on user time
      - pat_report -O mpi_rank_order ...
  - Can have a different metric for load balance
    - pat_report -O mpi_rank_order -s mro_metric=DATA_CACHE_MISSES ...

- Information in resulting report
  - Available if MPI functions traced (-g mpi)
  - Custom placement files automatically generated
    - Report provides quad core and dual core suggestions
      - 2, 4, and 8 cores per node
  - See table notes in resulting report for instructions on how to use

- Set MPICH_RANK_REORDER_METHOD environment variable
  - Set to numerical value or MPICH_RANK_ORDER file from pat_report

Rank Reorder Example (hycom)

```
pat_report -O load_balance

Table 2:  Load Balance across PE's by FunctionGroup

 Time % |        Time |     Calls |Group
        |             |           | PE[mmm]

 100.0% | 513.581345 | 368418.8 |Total
|-----------------------------------------
|  69.5% | 356.710479 |  37064.0 |USER
||----------------------------------------
||   0.3% | 441.604004 |  37064.0 |pe.73
||   0.3% | 395.835561 |  37064.0 |pe.62
||   0.0% |  23.942438 |  37064.0 |pe.184
||========================================
|  24.7% | 127.038044 | 325626.8 |MPI
||----------------------------------------
||   0.3% | 437.244595 | 239807.0 |pe.232
||   0.1% |  90.023179 | 317002.0 |pe.12
||   0.0% |  49.907519 | 317002.0 |pe.73
||========================================
|   5.8% |  29.832822 |   5728.0 |MPI_SYNC
||----------------------------------------
||   0.0% |  62.473245 |   5728.0 |pe.184
||   0.0% |  27.165827 |   5728.0 |pe.25
||   0.0% |  10.940857 |   5728.0 |pe.56
|=========================================
```

Example: -O mpi_rank_order (hycom)

```
Notes for table 1:

    To maximize the load balance across nodes,
    specify a Rank Order with small Max and Avg USER Time
    per node for the target number of cores per node.

    To specify a Rank Order with a numerical value, set the environment
    variable MPICH_RANK_REORDER_METHOD to the given value.

    To specify a Rank Order with a letter value 'x', set the environment
    variable MPICH_RANK_REORDER_METHOD to 3, and copy or link the file
    MPICH_RANK_ORDER.x to MPICH_RANK_ORDER.


Table 1:  Suggested MPI Rank Order
                     USER Time per MPI rank

                Max              Avg   Max
          USER Time        USER Time   Rank

      1015754691532    820499583863    73

------------------------------------------------------------

       Four cores per node:  USER Time per node

 Rank               Max     Max/              Avg     Avg/  Max Node
Order         USER Time      SMP        USER Time      SMP  Ranks

    d   3441386576933    85.0%   3281998335454   100.0%  113,227,115,197
    0   3857929506520    95.3%   3281998335454   100.0%  49,112,174,236
    2   3911647317171    96.7%   3281998335454   100.0%  57,67,182,191
    1   4046815451585   100.0%   3281998335454   100.0%  72,73,74,75

------------------------------------------------------------

       Eight cores per node:  USER Time per node

 Rank               Max     Max/              Avg     Avg/  Max Node
Order         USER Time      SMP        USER Time      SMP  Ranks

    d   6657050297152    82.8%   6563996670908   100.0%  130,195,65,214,136,178,190,0
    0   7315118136737    91.0%   6563996670908   100.0%  18,50,81,112,143,174,205,236
    2   7499444177191    93.3%   6563996670908   100.0%  30,32,93,94,155,156,217,218
    1   8036827543002   100.0%   6563996670908   100.0%  72,73,74,75,76,77,78,79
```

Example: File MPICH_RANK_ORDER.d (hycom)

```
#   The custom rank placement in this file is the one labeled 'd'
#   in the report from:
#
#     pat_report -O mpi_rank_order \
#        /home/users/ldr/ldr/COE_Workshop/hycom/090921P+hycomBase.ap2
#
#   It targets multi-core processors, based on Time in USER group
#   collected for:
#
#     Program:     hycom.2009Sep10.x
#     Number PEs:  249
#     Cores/Node:  4
#
#   To use this file, copy it to MPICH_RANK_ORDER and set the
#   environment variable MPICH_RANK_REORDER_METHOD to 3 prior
#   to executing the program.
#
46,126,32,176,109,224,48,243,39,142,154,220,137,21,174,140
36,151,155,242,15,219,133,177,110,108,134,100,25,118,132,148
130,195,65,214,136,178,190,0,61,141,54,167,162,161,189,122
111,183,35,3,163,129,50,199,93,84,88,29,246,26,153,168
38,196,182,210,156,30,51,5,81,231,64,159,24,179,49,239
104,95,175,143,206,120,152,215,80,217,135,4,13,31,34,228
37,169,66,211,157,83,172,203,92,226,53,234,201,86,188,7
180,238,52,139,138,229,33,193,45,194,94,166,207,205,173,185
63,204,18,11,14,164,97,241,131,123,99,22,102,101,98,149
40,107,223,85,103,202,76,212,82,247,67,70,124,208,79,144
105,235,89,160,119,87,78,192,181,10,55,127,20,221,77,225
191,9,44,209,23,106,96,233,60,187,17,146,170,244,57,145
112,150,43,117,236,216,56,6,47,8,19,121,116,12,58,198
16,27,42,186,158,230,218,248,41,1,245,165,62,200,59,213
114,2,91,28,128,125,75,232,222,147,90,71,171,69,72,240
113,227,115,197,237,68,74,184,73
```

Custom grid_order

```
$ ./grid_order

Usage: grid_order -C|-R [-P|-Z] -g N1,N2,...
                  -c n1,n2,... [-o d1,d2,...]
                  [-m max] [-n ranks_per_line] [-T] [i1 i2 ...]

   This program can be used to generate a rank order list for an MPI
   application that uses communication between nearest neighbors
   in a grid.  Note that this grid is a 'virtual' topology in the
   application's logic, not the physical topology of the machine
   on which it executes.  But it is assumed that ranks in the
   list will be packed onto machine nodes in the order given.

   You must specify either -C or -R for column- or row-major numbering.
   For example, if the application uses a 2 or 3 dimensional grid, then
   use -C if it assigns MPI rank 1 to position (1,0) or (1,0,0), but
   use -R if it assigns MPI rank 1 to position (0,1) or (0,0,1).
   To see the difference, compare the output from:
     grid_order -C -g 4,6
     grid_order -R -g 4,6
   The terms seem backwards if (1,0) is interpreted as x,y coordinates,
   but natural if interpreted as array indices in Fortran or C.
   Their usage here follows the definition of row-major numbering
   for a 'Cartesian virtual topology' in the MPI standard.

   For an application based on an N by M grid that uses column-major
   numbering and is run on six-core processors, either of the options:
      -C -c 2,3 -g N,M
      -C -c 3,2 -g N,M
   will produce a list of ranks suitable for the MPICH_RANK_ORDER file,
   such that blocks of 6 nearest neighbors are placed on each processor.
   If the same application is run on nodes containing two six-core
   processors, you could use -c 3,4 or -c 4,3. If possible, order the
   -c numbers so that each evenly divides the corresponding -g number.

   For an N by M by L grid with row-major numbering, and nodes with
   two six-core processors, one of the following can be used:
      -R -c 2,2,3 -g N,M,L
      -R -c 2,3,2 -g N,M,L
      -R -c 3,2,2 -g N,M,L

…
```

Documentation for the Cray Performance Toolset

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Programming Environments Director
Cray Inc.

Accessing Software Versions

- Software package information
  - Use **avail**, **list** or **help** parameters to module command
  - '**module help perftools**' shows release notes

- craypat version (same for pat_build, pat_report, pat_help)

  % pat_build –V

  CrayPat/X: Version 5.1 Revision 6438 12/10/10 13:37:21

- Cray Apprentice^2 version
  - Displayed in top menu bar when running GUI

Release Notes

```
ldr@crow:~> module help perftools/5.1.2

----------- Module Specific Help for 'perftools/5.1.2' ------------


===================================================================
Perftools 5.1.2
===============

Release Date: September 16, 2010

==================================================================
A license key must be installed on a FLEXnet server prior to using
perftools
==================================================================

Purpose:
--------

Differences between CrayPat 5.1.1 release and 5.1.2 release
-----------------------------------------------------------
CrayPat 5.1.1 release revision: 3618
CrayPat 5.1.2 release revision: 3746


Bugs closed since 5.1.1 release (August 19, 2010)
-----------------------------------------------
. . .

Known Problem(s)
----------------
. . .

Product and OS Dependencies:
----------------------------
 . . .
```

Online Information

- User guide
  - http://docs.cray.com
  - Click on “Latest Docs” and choose “Performance Tools 5.0”

- Man pages

- To see list of reports that can be generated

```
% pat_report -O -h
```

- Notes sections in text performance reports provide information and suggest further options

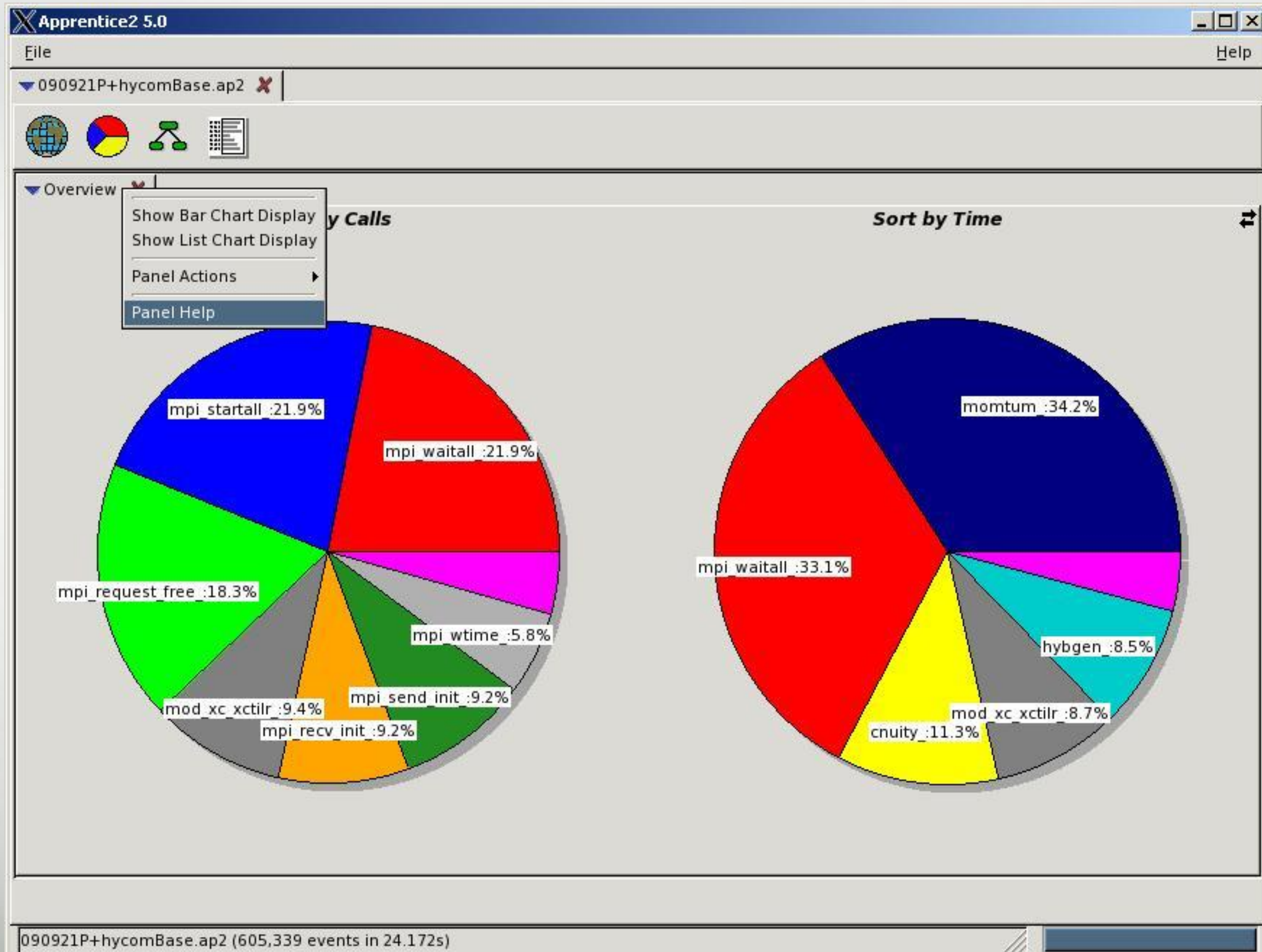
Online Information (2)

- Cray Apprentice^2 panel help
- pat_help – interactive help on the Cray Performance toolset
- FAQ available through pat_help

Man Pages

- **intro_craypat**(1)
  - Introduces the craypat performance tool
- **pat_build**
  - Instrument a program for performance analysis
- **pat_help**
  - Interactive online help utility
- **pat_report**
  - Generate performance report in both text and for use with GUI
- **hwpc**(3)
  - describes predefined hardware performance counter groups
- **papi_counters**(5)
  - Lists PAPI event counters
  - Use papi_avail or papi_native_avail utilities to get list of events when running on a specific architecture

Cray Apprentice^2 Panel Help



Top of Default Report from APA Sampling

```
CrayPat/X:  Version 5.0 Revision 2631 (xf 2571)  05/29/09 14:54:00

Number of PEs (MPI ranks):      48
Number of Threads per PE:       1
Number of Cores per Processor:  4

Execution start time:   Fri May 29 15:31:49 2009
System type and speed:   x86_64  2200 MHz
Current path to data file:
  /lus/nid00008/homer/sweep3d/sweep3d.mpi+samp.rts.ap2  (RTS)

Notes:
    Sampling interval was 10000 microseconds (100.0/sec)
    BSD timer type was ITIMER_PROF

  Trace option suggestions have been generated into a separate file
  from the data in the next table.  You can examine the file, edit
  it if desired, and use it to reinstrument the program like this:

            pat_build -O sweep3d.mpi+samp.rts.apa
```

pat_help

- Interactive by default, or use trailing '.' to just print a topic:
- New FAQ craypat 5.0.0.
- Has counter and counter group information

% pat_help counters amd_fam10h groups

pat_help Example

```
 The top level CrayPat/X help topics are listed below.
A good place to start is:

    overview

If a topic has subtopics, they are displayed under the heading
"Additional topics", as below.  To view a subtopic, you need
only enter as many initial letters as required to distinguish
it from other items in the list.  To see a table of contents
including subtopics of those subtopics, etc., enter:

    toc

To produce the full text corresponding to the table of contents,
specify "all", but preferably in a non-interactive invocation:

    pat_help all . > all_pat_help
    pat_help report all . > all_report_help

Additional topics:

  API                        execute
  balance                    experiment
  build                      first_example
  counters                   overview
  demos                      report
  environment                run

pat_help (.=quit ,=back ^=up /=top ~=search)
=>
```

pat_help FAQ

```
pat_help (.=quit ,=back ^=up /=top ~=search)
=> FAQ
  Additional topics that may follow "FAQ":

    Application Runtime                     Miscellaneous
    Availability and Module Environment     Processing Data with pat_report
    Building Applications                   Visualizing Data with Apprentice2
    Instrumenting with pat_build

pat_help FAQ (.=quit ,=back ^=up /=top ~=search)
=> I
  Additional topics that may follow ""Instrumenting with pat_build"":

        1. Can not access the file ...
        2. ERROR: Missing required ELF section 'link information' from the program 'FILE'.
        3. ERROR: Missing required ELF section 'string table' from the program '...'.
        4. FATAL: The link information was not found in the .note section of ...
        5. How can I find out the text size of functions?
        6. How can I list trace points from my instrumented binary?
        7. How can I lower the size of data files with pat_build?
        8. How can I NOT instrument some of my object file(s)?
        9. How do I get MPI rank order suggestions?
       10. How do I specify a directory containing object files?
       11. My error messaage is "xyz can not be traced because ... not writable"
       12. Problems with instrumented programs using both MPI and OpenMP?
       13. User sampling with compiler hooks present is not allowed
       14. WARNING: Entry point 'FUNCTION' can not be traced because it is a locally
           defined function
       15. WARNING: The function 'FUNCTION' can not be traced because a trace wrapper
           was not successfully created
       16. What is APA?
       17. Why am I getting an error with userTraceFunctions.c?
       18. Why does my binary take longer to run when using 'pat_build -u'?

pat_help FAQ "Instrumenting with pat_build"
(.=quit ,=back ^=up /=top ~=search) =>
```

FAQ Example

```
pat_help FAQ "Instrumenting with pat_build"
(.=quit ,=back ^=up /=top ~=search) => 4


    FATAL: The link information was not found in the .note section of ...

        If an executable is compiled and linked without the xt-craypat module
    loaded, then it will not contain link information needed by pat_build,
    which will issue an error message and exit.

        To verify that an executable was built with the link information that
    pat_build requires, use

           readelf -S $executable

        It should show a .note section with a size of several kilobytes, say
    section 19, and the output from

           readelf -x 19 $executable

        should contain the string 'Cray Inc' and library paths.


pat_help FAQ "Instrumenting with pat_build"
(.=quit ,=back ^=up /=top ~=search) =>
```

Hands-on Tasks

1. Generate an “.apa” file and a sampling report from your application
2. Read the “.apa” file and add I/O instrumentation
3. Use the .apa file to generate a profile of the application
4. Look at the sampling report and identify areas where work is concentrated. Using the CrayPat API add instrumentation around the important loop(s)
5. Generate a second profile of the application with code regions
6. Obtain MFLOPS, TLB Utilization, Cache Hit/Miss ratios (L1 and L2), Cache utilization (L1, and L2), FP Mix, and Vectorization information for the main regions and functions of the application
7. Visualize the performance file (.ap2) with Cray Apprentice2 and identify the most imbalanced function or region of the application
8. Generate a trace file of the application (if the application is large, limit the size of the trace file)
9. Visualize the trace file with Cray Apprentice2
10. Optimize your application with the data that you collected

Performance Measurement and Visualization on the Cray XT

Questions / Comments
Thank You!